RADIOACTIVE WASTE TREATMENT AND CONDITIONING USING PLASMA TECHNOLOGY PILOT PLANT: TESTING AND COMMISSIONING

LOJI PERINTIS PERAWATAN DAN PENYESUAIAN SISA RADIOAKTIF MENGGUNAKAN TEKNOLOGI PLASMA: PERCUBAAN DAN PENTAULIAHAN

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Abstract

Plasma pilot plant was commissioned for research and development program on radioactive waste treatment. The plant is equipped with a 50kW direct current of non-transferred arc plasma torch which mounted vertically on top of the combustion chamber. The plant also consists of a dual function chamber, a water cooling system, a compress air supply system and a control system. This paper devoted the outcome after testing and commissioning of the plant. The problems arise was discussed in order to find the possible suggestion to overcome the issues.

Abstrak

Loji perintis plasma telah ditauliahkan bagi program penyelidikan dan pembangunan dalam perawatan sisa radioaktif. Loji ini dilengkapi dengan 50kW penunu plasma jenis arca tidak boleh dipindahkan berarus langsung yang dipasangkan di atas kebuk pembakaran. Loji ini turut merangkumi kebuk dwi fungsi, system penyejukan cecair, pemampat udara dan system kawalan. Kajian ini menumpukan pada dapatan selepas ujian dan pentaulian loji. Masalah yang timbul dibincangkan dalam usaha untuk mencari cadangan terbaik untuk mengatasi isu-isu yang dihadapi.

Keywords: Plasma pilot plant, radioactive waste treatment, direct current, non-transferred arc plasma torch

INTRODUCTION

Thermal plasma processing is one of technologies that can be used to decrease the amount of radioactive waste stored and also safe to the environment. Research and development of plasma now focuses on the environmental clean-up areas. This involves in gasification of municipal wastes and used tires as an alternative energy source, destruction and disposal of toxic and hazardous medical, chemicals and nuclear wastes such as power plants (Chang 2009). Industries take in the plasma technology as the advantage of treating and melting incombustible materials owing to its high temperature properties and produced immobilized and stable end product suitable for long term storage or disposal (A. Mosse 2012).

2.0 PLASMA TECHNOLOGY

2.1 Fundamental background

Plasma technology is one of the most effective methods for solid waste treatment with relatively small and controllable amounts of toxic by-products will be discharged. Design of plasma system is interdependent with the type of material to be treated and type of thermal processes including, melting, coating, waste destruction, vitrification or pyrolysis (E. Gomez 2008). Basically this intent to destroy the organic fraction and convert the inorganic fraction into an inert silicate slag, or glass that can either be advantageously reused, or harmlessly disposed of in an inert landfill.

Thermal plasma or also known as low temperature plasma use heated gas with temperature 30 000 – 50 000 °C produce by plasma torches or plasmatron which commercially used in various industrial processes (A. Mosse 2012). During operational, the electricity is transformed into thermal energy by means of electric discharges from cathode to anode within a water-cooled torch. The plasma will produce a gas which crosses the boundary layer between the gas column and the anode inner surface. Then, it directly pushed to the downstream by the pressure of the gas flow resulting in plasma jet at the outlet of the torch. The arc produced inside the chamber is established between the axial cathode and an annular anode.

2.2 Design system

In order to optimize and control the thermal treatment of the waste and to preclude the secondary formation of toxic substances, the reaction products are quenched which the temperature is sharply decreased to 300–400 ºC by introducing air as a cooling agent through a specially developed quenching ring. In term of vitrification, a special designed direct current (DC) non-transferred plasma torch was used with a tungsten cathode and two nozzle shaped copper anodes set at different axial distance from cathode tip, to generate long lifetime and highly stable plasma jet. In order to maintain the plasma torch in a stationary state at a reasonable temperature and to limit the electrode wear, each electrode and the torch body are water cooled independently. In overall, the benefits are more efficient use of energy, lower capital costs, substitution of exhaustible fossil fuels and in rendering small capacity plants economically viable reversing of the "economies of scale". The use of plasma technology is also expected to have environmental benefits since total gas flow rate is much smaller compared with conventional heating systems.

3.0 PLASMA PILOT PLANT PROCESS

Basically, there are 2 types of plasma torch that is transferred arc where one of the electrodes is usually the material to be treated while non-transferred arc plasma is where the arc is contained inside a plasma torch and the plasma jet exiting the torch is used for processing. In the DC torch, the electric arc is formed between the electrodes which can be made of copper, tungsten, graphite, molybdenum, silver etc, and the thermal plasma is formed from the continual input carrier gas. In this thermal plasma pilot process, non-transferred arc torch are used to treat low and intermediate level radioactive waste (LILW).

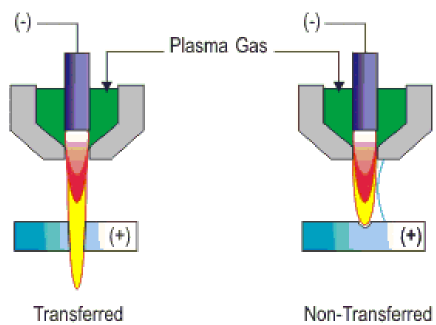

Figure 1: Comparison transferred and non-transferred arc torch

3.1 Non-transferred arc

The two main classes of plasma torches are called transferred and non-transferred torches. In former, the electric arc used to generate the plasma is maintained between one electrode of the torch (normally the cathode) and a piece of metal (or another conducting material) that one wants to cut or melts, located outside the torch. Those torches are typically used for metallurgical processes such as ferroalloy production or tundish heating. The other type, the non-transferred plasma torch, employs the two electrodes of the torch in order to maintain the electric arc. The electric arcs are strikes between the two electrodes of the torch and it is kept inside the torch. These torches are normally used for spraying, production of advanced materials and the treatment of hazardous wastes.

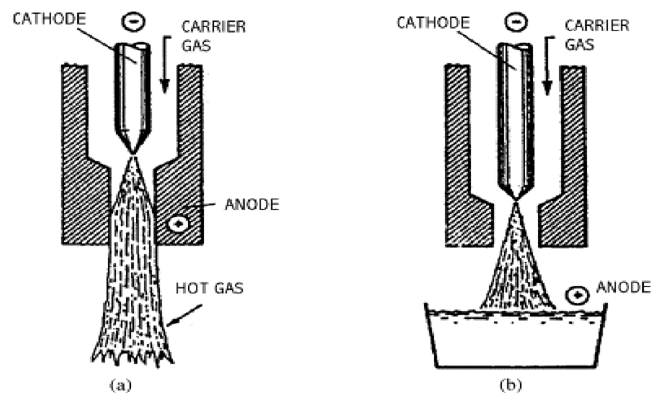

Figure 2: Different between transferred arc torch (a) and non-transferred arc torch (b) of plasma.

3.2 Component and process involved

The components that are involved in the system must follow standard requirement and specification to ensure the safety and functionality of the process. The component installed in the plant are plasma torch, dual-function chamber, cooling system, air pollution control unit, chiller, control and instrumentation system, piping and ducting system, power supply system in AC-DC converter mode, air compressor, exhaust fan, dryer, air reservoir, centrifugal pump, and thermocouples. Basically at air pollution control unit a set of equipment involved a blower, heat exchanger, primary filter, condenser, HEPA filter and chimney to comply air emission quality regulation.

Table 1 Types of component and its functions

Components	Functions
Plasma torch	Direct flow plasma generator.
Dual-function chamber	Samples are placement for combustion.
Air pollution control unit	
i. Blower	-Providing large air flow for primary cooling system.
ii. Heat exchanger	-Cooling high temperature gas from combustion chamber.
iii. Primary Filter	-Used for its relatively high remaining emission.
iv. Condenser	-Converting hot gas from exchanger system to liquid state.
v. HEPA filter	-Filter unwanted particles before air emission.
vi. Chimney	-Provide ventilation for air emission that safe to release.
Cooling system	Ensure the system safe to be run to avoid the plasma torch from melting.
Chiller	Cool the air in their respective space.

Control and instrumentation	Control the flow on the pilot plant and data recording purpose.
Piping and ducting system	Connection between subsystems and ducting it by using flange.
Power supply system	Supply power to the system.
Air Compressor	Converting power to potential energy which stored as pressurize air
Exhaust fan	Ensure the system in negative pressure to avoid liquid leaking from any edges or sampling point.
Dryer	To dry the gas/air come from the compressor before enter the combustion chamber due to the safety.
Air reservoir	As a storage tank for the gas that comes from air compressor before deliver it to the combustion chamber.
Centrifugal pump	Operation on the principle of centrifugal force.
Thermocouples	Temperature measurement instrument.

3.3 Pilot Plant Specification

Pilot plant run at fixed voltage of 300V and the current is adjusted to certain value as a power supply to the system. The critical parameter temperature and pressure in the system are monitored and recorded from the control room. This system comply negative pressure condition for avoiding possibilities of liquid leaking from any edges or sampling point. There are 4 valves connected in the combustion chamber which is 2 valves supply argon gas and other 2 valves supply water vapor. Gas from the thermal plasma plant process is safe to be released through chimney after passing air pollution control unit. The complete final product of immobilization glass are already safe to environment because the radioactivity contain in the sample are in immobilization state as it cannot release the radiation itself to the surrounding.

The overview of thermal plasma pilot plant control system are shown below:

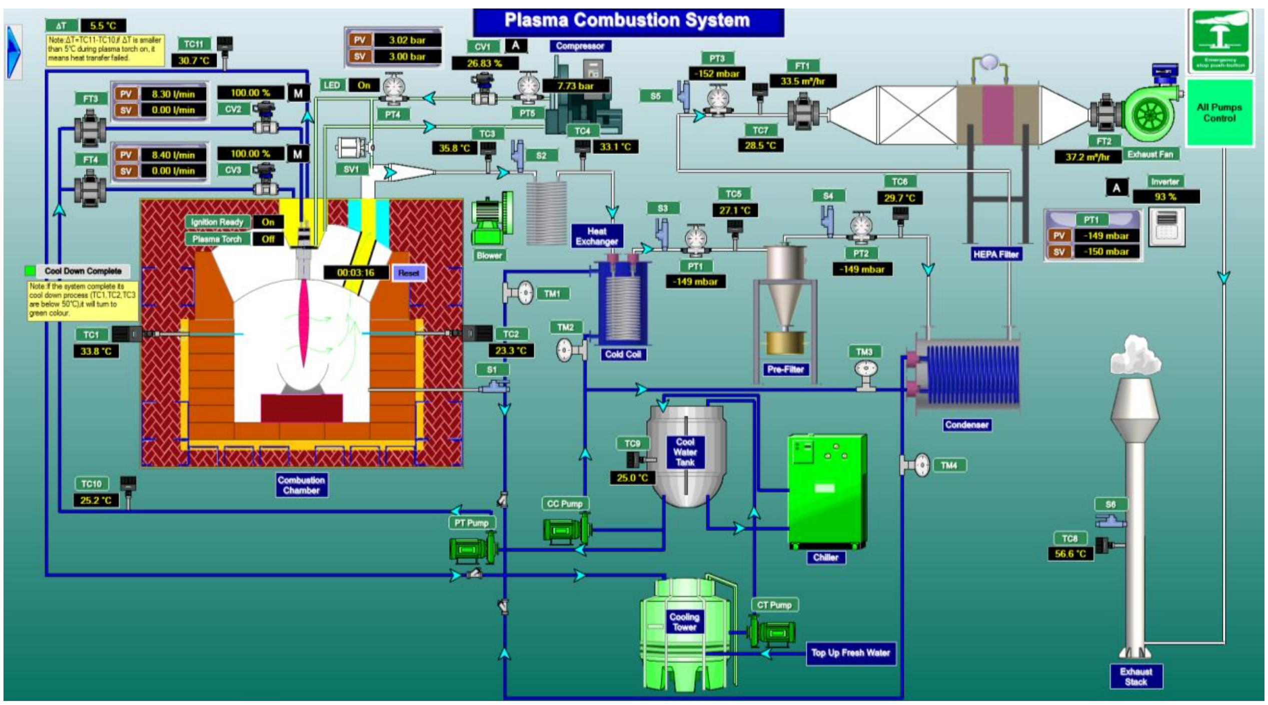

Figure 3: Thermal Plasma Pilot Plant Process

4.0 PLANT TESTING

Low and intermediate level radioactive waste undergo vitrification process associated with the melting of samples into a glassy product inside the chamber. Due to the chemical composition of the radioactive waste, melting process requires a temperature higher than 1400°C. In this scheme, the sample is in contact directly with the high energy intensity arc resulting in a very efficient heat transfer from the arc to the ash. The temperature plasma arc produced on the pilot plant was not directly measured by the online control system during operation. Determination of plasma jet temperature can be carried out using calorimetric calculation method.

Table 2 Data collected for air consumption based on current set

P_{min}, bar	P,bar	P_{max}, bar	Air consumption min, g/s	Air consumption operation, g/s	Air consumption max, g/s	Current Set, A
2.9	3.4	5.0	3.8	4.5	6.6	100
3.4	3.8	5.8	4.4	5.0	7.6	120
4.2	4.6	6.5	5.5	6.0	8.5	140
5.0	5.3	7.0	6.5	7.0	9.2	160

4.1 Determination of plasma jet temperature

4.1.1 for minimum value of current (100A)

Table 3 Data collected for minimum value current

Current and Voltage	
Current (A)	100 A
Voltage (V)	300 V
Power supply (W)	30000 Watt
Temperature of cooling water	
Inlet	17.3 °C
Outlet	11.4°C
Water flow rate	0.2725 liter/s
Air flow rate	4.5 g/s

Heat loss at outlet, Q_{loss}

Q_{loss} = $m_{water} \times c_p \times \Delta T$

= 0.2725 kg/s x 4189 J/kg.K x (17.3-11.4) K

= 6734.865 J/s

Nett power, N

N = Power - Q_{loss}

= 30 000 W – 6734.865 W

= 23265.135 W

Enthalpy of plasma flow, h_{plasma}

$$h_{plasma} = \frac{N}{G} + h_{inlet}$$

= (23265.135 J/s / 4.5 g/s) x (1000 g/kg) + 300616 J/kg

= 5,470,646 J/kg

*h_{air} at 27 ^{0}C is 300616 J/kg

Average temperature of plasma jet, T_{plasma}

$$T_{plasma} = 1596.3 \times \ln\left(\frac{h_{plasma}}{1000}\right) - 10305$$

$$= 1596.3 \times \ln\left(\frac{5470646}{1000}\right) - 10305$$

$$= 3434.597\ K\ @\ 3161.45\ ^{o}C$$

4.1.2 for maximum value of current (160A)

Table 4 Data collected for maximum value current

Current and Voltage	
Current (A)	160 A
Voltage (V)	300 V
Power supply (W)	48000 Watt
Temperature of cooling water	
Inlet	17.3 °C
Outlet	11.4°C
Water flow rate	0.2725 liter/s
Air flow rate	7.0 g/s

Heat loss at outlet, Q

$$Q = m_{water}\, C_p\, \Delta T$$

$$= 0.2725\ kg/s \times 4189\ J/kg.K \times 5.9$$

$$= 6\,734.865\ W$$

Nett power, N

$$N = \text{Power supply} - \text{Heat loss}$$

$$= 48\,000 - 6\,734.865$$

$$= 41\,265.140\ W$$

Enthalpy of plasma flow, h_{plasma}

$$h_{plasma} = h_{flow} + h_{inlet}$$

$$= \frac{N}{G} + h_{air}$$

$$= \frac{41\,265}{7.0}(1000) + 300\,616$$

$$= 6\,195\,616\ J/kg$$

*h_{air} at 27 ^{0}C is 300616 J/kg

Average temperature of plasma jet, T_{plasma}

$$T_{plasma} = 1596.3 \times \ln\frac{h_{plasma}}{1000} - 10305$$

$$= 1596.3 \times \ln\frac{6\,195\,616}{1000} - 10305$$

$$= 3\,633.248\ K\ @\ 3360\ ^{o}C$$

Determined Nett power when T_{plasma} = 6000K by using reverse calculation

Based on the theoretical, the temperature of plasma was 6000K. Therefore this reverse calculation was to determined the Nett power are needed to produce T_{plasma} = 6000K.

Enthalpy of plasma flow, h_{plasma}

$$T_{plasma} = (1596.3) \times \ln\left(\frac{hplasma}{1000}\right) - 10305$$

$$6000 = (1596.3) \times \ln\left(\frac{hplasma}{1000}\right) - 10305$$

$$h_{plasma} = 27\ 287\ 936.58 \text{ J/kg}$$

Enthalpy of flow, h_{flow}

$$h_{plasma} = h_{flow} + h_{inlet}$$

$$27\ 287\ 936.58 = h_{flow} + 300616$$

$$h_{flow} = 26\ 987\ 320.58 \text{ J/kg}$$

*h_{inlet} = h_{air} of Pressure = 1 bar , Temperature = 27°C

Nett Power, N

$$h_{flow} = \frac{N}{G}$$

$$26\ 987\ 320.58 = \frac{N}{4.5}(1000)$$

$$\text{Nett Power} = 121{,}442.94 \text{ W} \approx 121.45 \text{ kW}$$

4.2 Installation Process

An expert from International Atomic Energy Agency (IAEA) invited during installation process of plasma torch at the combustion chamber. The plant consists of a dual function chamber, a water cooling system, a compress air supply system and a control system.

Figure 4: The installation process briefing by expert from Russia.

4.3 Testing with Oil Sludge

<u>Sample</u>

Materials : Raw Oil Sludge (1 kg) + Powder glass (0.5kg) + Crush glass (0.5kg)

Nuclide : Radium 226, Radium 228

Activity : 250 Bq/g (Radium 228), 318 Bq/g (Radium 226)

Container : Graphite

Electric supply (main power) : 0.4 kWh

Total Time Running : 720 second.

Figure 5 shows the sample and final product after 12 minutes of testing. Based on the observation, the glass on the top was fully melt and attached with oil sludge. The thickness of graphite crucible seem decreasing on the thickness, this probably because of the time of heat exposed to the crucible.

(a)

(b)

Figure 5: (a) The sample of oil sludge change to partial immobilization glass after running about 12 minutes (b) The oil sludge and sand samples after plasma testing

Table 5: Data of the plasma non-transferred arc torch plant testing with sample in 12 minutes.

Time Taken, (s)	Temperature, (°C)	Current, (A)	Voltage, (V)	Power, (kW)
120	-	100	300	30.0
150	450	125	300	37.5
330	454	150	325	48.7
510	515	135	320	43.2
630	562	130	320	41.6
720	565	125	320	40.0

Figure 6 show the correlation between parameter of temperature, voltage and current against time during testing with oil sludge. Parameter for current was set in increasing order from range of 100A to 150A to achieve highest temperature. The graph represent data from table 5, collected during testing with the sample for 12 minutes.

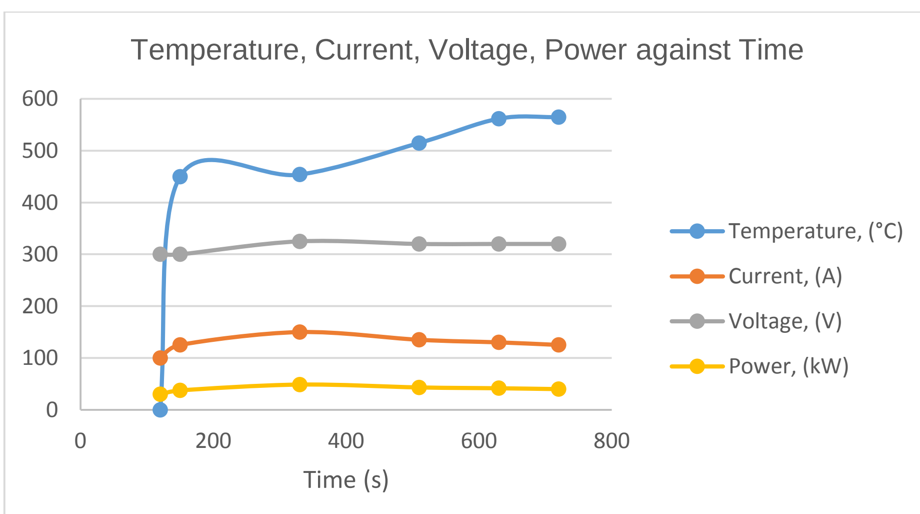

Figure 6: Correlation between temperature, voltage and current with time for oil sludge sample

Operating of the thermal plasma plant stop at minutes of 12 when the pressure of air compressor becomes 1 bar. The pressure drop as shown in figure 7. This problem results of gas consumption that produced by the air compressor are not enough compared the gas required in the system.

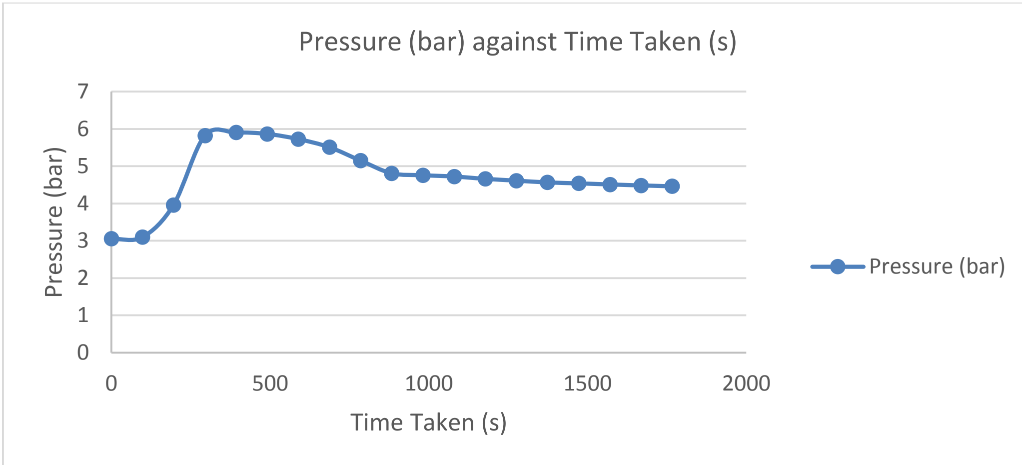

Figure 7: Correlation between pressure and time for oil sludge sample

5.0 PROBLEMS DETECTED DURING COMMISSIONING ACTIVITIES

List of problems during testing and commissioning activity was presented, the team discussed the possible action to be taken in order to improve the technical system. The table show improvement work suggested be done to overcome the current problem face by the system.

Table 6: Testing results for thermal plasma pilot plant and suggestions for improvement.

Components	Problems	Suggestion
Air Compressor	The gas consumption is not enough compared to the gas required in system due to the low power and efficiency of the pump of the air compressor.	Change with new one that has enough power pump to generate gas consumption more than 3 bar continuously.
Combustion Chamber	The chamber is not fully vacuum because the gas still can pass out through the chamber during operation.	Due to the safety requirement, the lining of the chamber should be added to make sure the chamber fully in vacuum state and the gas not release out through the chamber. Modified the chamber with transparent door.
Chimney	The gas release will come in into the plant air surrounding because the roof of the location is higher than the chimney.	Increase the height of the chimney higher than the roof of the plant to avoid the gas releases come in into the plant air surrounding.
Exhaust Fan	Not enough power to pull out the pressure out of the system to make the system of the plant under negative pressure.	Increase the power of the exhaust fan
HEPA Filter	The yellowish gas release from the chimney.	-Replace the pore of the filtrate with smallest one to reduce emission -Add the scrubber for gas treatment.

Software System	Results shows by the system was not synchronize with temperature meter.	-System calibration.
Plasma Torch	Actual pressure and temperature of the plasma torch cannot be measure.	Introduce temperature and pressure suitable for the system.

Based on product observation, plasma flame cannot penetrate until the bottom of the container. The possible factors sample are not completely vitrified is because of the short exposure time to the flame and the matrix composition of the sample. Besides that, another issue arise during testing is presence of positive pressure which results of gas leaking and vibration on the piping system. In order to achieve negative pressure, changing of the exhaust fan with another vacuum pump with higher power of suction.

6.0 CONCLUSIONS

The calculation conducted using calorimetric method determines the plasma jet temperature at minimum and maximum value of current. At minimum current of 100A and constant voltage 300V the plasma torch produced a plasma jet at temperature approximately 3161^{o}C. While, at maximum current 160A during the operational the plasma torch can produced a plasma jet at temperature about 3360^{o}C. Based on reverse calculation by calorimetric method, about 121.45 kW number of power required to produce 5726.85^{o}C of plasma jet. During testing and commissioning of plasma torch system the team highlighted three main issue; the system not operate in negative pressure, plasma flame cannot penetrate to the bottom of the sample and the actual temperature of plasma flame calculated are cannot be proved. As suggested during testing the vacuum pump, air compressor and filter has changed. The combustion chamber was installed with the lining and chimney position has been modified.

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